

## INFRARED CORONAL LINES. II. OBSERVATION OF [Si x] $\lambda 1.43 \mu$ AND [Mg viii] $\lambda 3.03 \mu$

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### ABSTRACT

The wavelengths and intensities of the coronal lines of the ions  $\text{Si}^{9+}$  and  $\text{Mg}^{8+}$ , resulting from the airborne observation of the November 12, 1966, total solar eclipse, are given

### I. INTRODUCTION

It has been suggested (Münch 1966) that the ions  $\text{Si}^{9+}$ ,  $\text{Si}^{8+}$ , and  $\text{Mg}^{7+}$  should give rise to coronal lines with sufficiently high intensity to be detected without difficulty. These lines may provide a useful tool to study the physical conditions in the corona and, therefore, when the opportunity to observe the total solar eclipse of November 12, 1966, from the NASA aircraft "Galileo" became available, it was decided to carry out an airborne experiment for their observation. Since the wavelengths of the lines cannot be predicted with sufficient precision to evaluate the effects of telluric absorption on their intensities at ground locations, a first observation from a high-altitude aircraft offered definite advantages over other possible means.

On the basis of the signal-to-noise ratios evaluated earlier (Münch 1966) and the duration of the eclipse, the scope of the experiment was limited to the detection of the two strongest predicted lines, the determination of their wavelengths and the measurement of their approximate strengths.

It should be pointed out that at the May, 1965, total solar eclipse, Mangus and Stockhausen (1966) carried out an airborne observation of the corona over the  $1.0\text{--}3.5\text{-}\mu$  spectral range by means of a dynamic Michelson interferometer. Their spectra show a "very weak but persistent" emission feature superposed on a strong continuum, "that might possibly be identified as the 6990 kayser line of Si x."

### II. INSTRUMENTATION

Because of limitations in the time and in the resources available to prepare the experiment, it was decided to utilize, with a minimum of modifications, the 50-cm Ebert-Fastie spectrometer recently used by the authors for observations of stellar spectra in the PbS region (McCammon, Münch, and Neugebauer 1967). The image-forming optics was an 8-inch parabolic mirror with 35.5-inch focal length, mounted horizontally in a rigid frame, which was illuminated by a gyro-stabilized heliostat, as indicated in Figure 1. The cross-section of the incident beam was limited by the 5.5-inch-diameter circular aircraft window. The spectrometer was attached at the Newtonian focus of this primary mirror. In order to collect as much coronal light as possible, the entrance slit was made in the form of a  $90^\circ$  segment of a circular arc with 4.3 mm radius (the radius of the solar image). The slit width of 0.50 mm set the spectral resolution to be  $26 \text{ \AA}$  in the first order at  $3 \mu$  and  $13 \text{ \AA}$  in the second at  $1.4 \mu$ . For the purpose of visual guiding, the brass plate containing the entrance slit was polished to be seen by reflection through a periscope. Immediately behind the slit, a chopper mirror, moving normally to the entrance beam at 5 c/s, deflected the light  $90^\circ$  to the Ebert mirror. This chopping scheme, together

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with the synchronous demodulation, provides a rectified output signal proportional to the difference between the intensities of radiation at two wavelengths separated by one spectral element. After dispersion by a 300 groove/mm grating, the light was brought to foci at two different exit slits, corresponding to the [Si x]  $\lambda 1.43 \mu$  and [Mg VIII]  $\lambda 3.03 \mu$  lines. These slits were made in the same form as the entrance slit by evaporating aluminium on the sapphire windows of the liquid nitrogen dewars inclosing the detectors. The dewars contained, besides  $0.5 \times 0.5$  mm lead sulfide cells, silicon f:0.6 lenses and short- and long-pass isolation filters. The detector for the weaker [Mg VIII] line received the entire beam emergent from the Ebert mirror, while that for the [Si x] line, in order not to cut into the beam of the weaker line, was illuminated through two  $45^\circ$  mirrors, which "saw" only about 20 per cent of the mirror. Each detector was followed by pre-amplifiers and synchronous demodulators, the recording of the final output being done

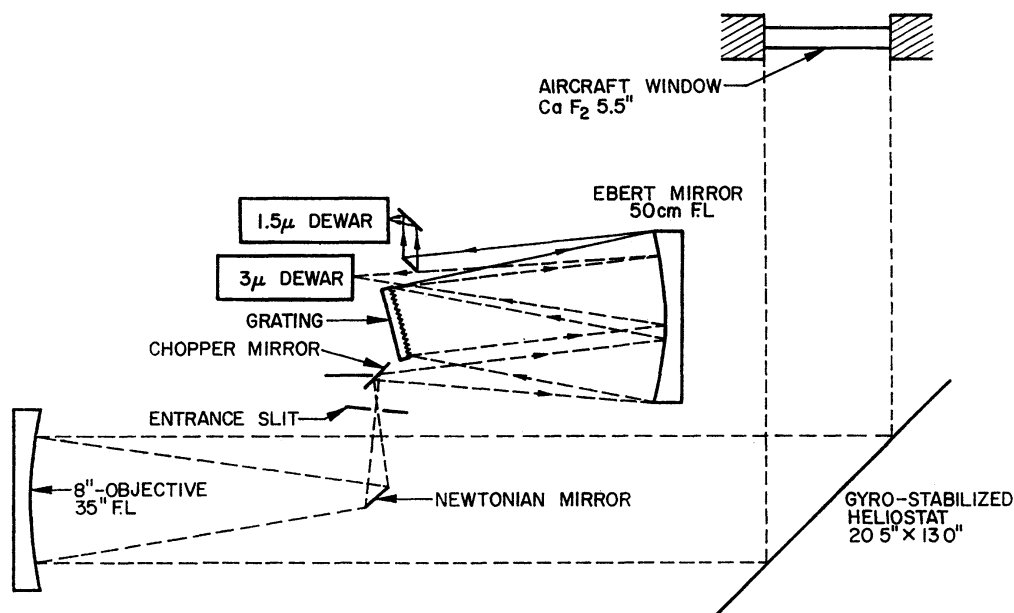


FIG. 1.—Schematic arrangement of the optical system

with a two-pen strip-chart recorder. The wavelength of the recorded spectra was established by fiducial marks of a marginal pen, activated by pulses from the micrometer grating drive.

### III. OBSERVATIONS

Three spectral scans were obtained during the 215 sec duration of the eclipse, with the slit oriented to match the eastern equatorial limb of the Sun, as indicated in Figure 2 (Plate 5). First an interval of  $150 \text{ \AA}$  was scanned around the predicted wavelength of the [Si x] line. Immediately after this was finished, the grating was manually rotated to bring the region of the [Mg VIII] line into view. About  $300 \text{ \AA}$  were then scanned in one direction and repeated in the opposite one. Each of the three scans contains two fiducial wavelength marks. The strip-chart recorder output for the two regions scanned is reproduced in Figures 3 and 4. The [Si x] line can be seen very clearly, with a signal to noise ratio on the order of 50:1. The background on which it appears is smooth, although a significant asymmetry between the short- and long-wavelength branches of the line (actually the derivative of the line shape) can be noticed. The signal to noise ratio of the [Mg VIII] line, shown by the average of the tracings obtained in the forward and backward scan directions, is at most 3:1. Besides cell noise, guiding irregularities



## PLATE 5

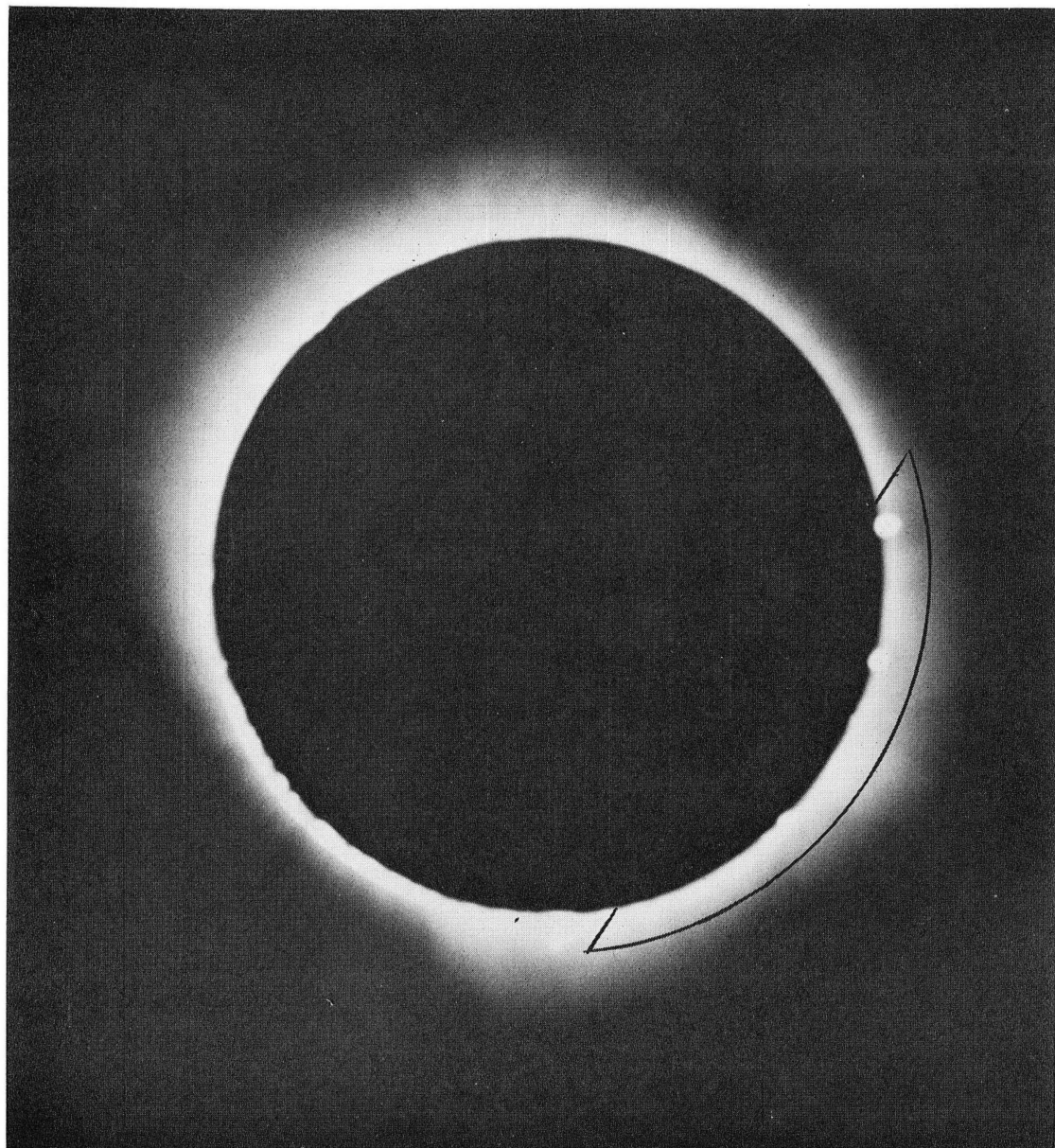


FIG. 2.—Position of the slit on the corona of Nov. 12, 1966. White light photograph by D. H. Menzel and W. N. Arnquist, of the Douglas Aircraft Co. Expedition, taken at Chiquata, Arequipa, Peru.

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combined with the presence of three active coronal regions on the slit may have contributed to the signal fluctuations.

#### IV. RESULTS

*a) Wavelengths.*—The wavelength calibration was established by illuminating the slit with a krypton discharge tube through diffusers. Tracings of the Kr lines at  $\lambda 1.4348$  and  $\lambda 1.5239 \mu$  which fall within the range scanned around the [Si x] and [Mg viii] lines,

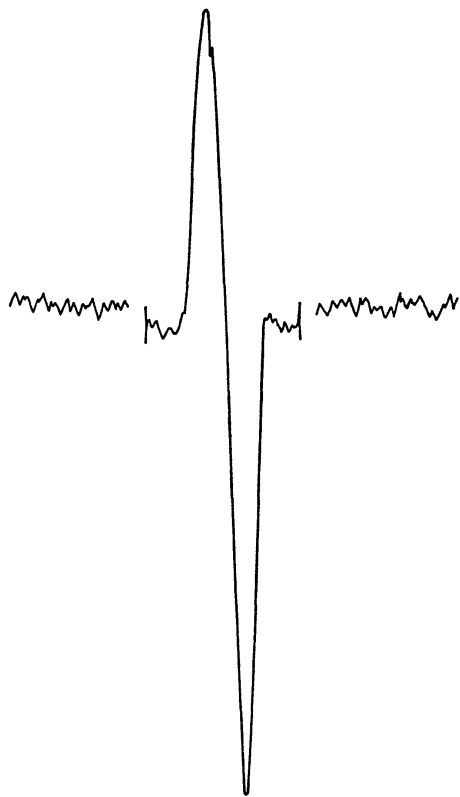


FIG. 3

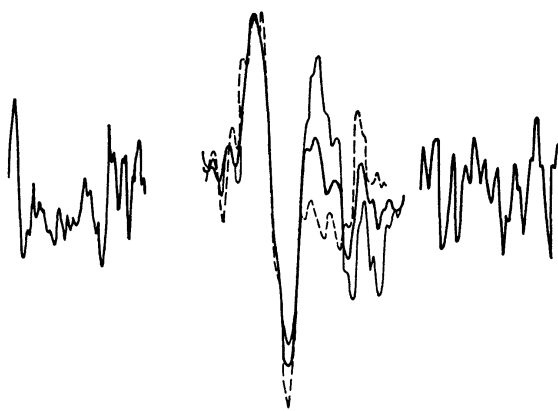


FIG. 4

FIG. 3—Tracing of the strip chart record of the [Si x]  $\lambda 1.4305 \mu$ -line profile. The beginning (*left*) and end (*right*) of the eclipse scan are indicated by short vertical bars. The system-noise level before and after the eclipse is indicated by the segments of tracing at the left and right of the line.

FIG. 4.—Reproduction of the scan records obtained for the [Mg viii]  $\lambda 3\ 0275\text{-}\mu$  line in the forward (*dashed line*) and backward (*thin line*) directions. The average profile is represented by the thick line. The system-noise level is indicated by the segments of tracing at the extreme right and left of the line, obtained before and after the eclipse.

were obtained immediately preceding and after the eclipse. These wavelength calibrations were done with the same amplifier gains, time constants (2 sec in all cases), and scanning speeds as used during the eclipse. The wavelengths of the two coronal lines have been estimated as follows:

$$\begin{aligned} \text{Si x: } \lambda_{\text{obs}} &= 1.4305 \pm 0.0004 \mu, & \lambda_{\text{pred}} &= 1.4310 \mu, \\ \text{Mg viii: } \lambda_{\text{obs}} &= 3.0275 \pm 0.0020 \mu, & \lambda_{\text{pred}} &= 3.0320 \mu, \end{aligned}$$

where the uncertainties have been derived from the internal agreement between the relative position of the two maxima and the zero-level crossing for each of the lines.

*b) Intensities.*—The calibration to determine the absolute intensities of the observed coronal lines was performed at the laboratory in Pasadena, unfortunately only after returning from the eclipse. The response of the spectrometer-detector system to a black body at temperatures of 750° and 1000° C was measured using an external 5 c/s chopper. The black body was focused on the entrance slit of the spectrometer by means of the same primary mirror used at the eclipse, but working off-axis instead of in the Newtonian arrangement. The detector system was operated in the laboratory under the same conditions and showed within 20 per cent the same noise levels and response to the Kr calibration lamp as during the eclipse. From the comparison of the deflections produced by the coronal lines and those obtained from the black body, it has been estimated that the radiative powers  $W$  of the coronal lines measured during the eclipse were

$$W(\text{Si}^{9+}) = 1.7 \times 10^{-10} \text{ watt},$$

$$W(\text{Mg}^{8+}) = 4 \times 10^{-11} \text{ watt},$$

where allowance has been made for 30 per cent loss in reflection and transmission at the  $\text{CaF}_2$  window, the heliostat, and the secondary Newtonian flat. No correction has been made for atmospheric attenuation in the laboratory or in the residual atmosphere above the aircraft. Nonetheless, considering the time elapsed between the two measurements, possible variations in the responsivity of the detectors and differences in collimation and alignment conditions could make the power estimates given above uncertain by factors as large as 2.

In order to derive the specific intensity  $I$  of the lines from the observed powers, an assumption regarding the distribution of coronal line intensity over the exit slit has to be made. If the intensities were uniform over the entire slit

$$I_{\text{av}}(\text{Si}^{9+}) = 3 \times 10^{-7} \frac{\text{watt}}{\text{cm}^2 \text{ sterad}}, \quad I_{\text{av}}(\text{Mg}^{7+}) = 0.7 \times 10^{-7} \frac{\text{watt}}{\text{cm}^2 \text{ sterad}}.$$

Actually, the distribution of coronal line intensity is generally concentrated in a band extending  $\pm 30^\circ$  in heliographic latitude. In addition, the three active regions shown in Figure 2 (Plate 5), a white light photograph of the corona of November 12, 1966, were covered by the slit and contributed, probably predominantly, to the measured powers. The line intensities corresponding to the quiet equatorial at maximum could be thus smaller than the values given above by a factor between 3 and 5.

## V. DISCUSSION

The determination of the wavelength of the  $[\text{Si x}]$  and  $[\text{Mg viii}]$  lines allows us to make a definite statement regarding the possibility of observing them from a ground location, either during a total solar eclipse or with appropriate coronagraphic equipment. The position of the  $[\text{Si x}]$  line in the solar spectrum, as observed from Mount Wilson, is illustrated in Figure 5. Recalling that the expected width at half-power of the  $[\text{Si x}]$  line is 3 Å, nearly equal to the probable error of the wavelength determination; it can be seen from Figure 5 that the line cannot be completely absorbed by the strong  $\text{H}_2\text{O}$  telluric line at  $\lambda 1.4308 \mu$ . Rather there is a probability near  $\frac{1}{2}$  that the line will reach ground without attenuation. The position and uncertainty of the  $[\text{Mg viii}]$  in the solar spectrum are indicated in Figure 6, where it can be seen that about half of the uncertainty range is overlapped by the  $\text{H}_2\text{O}$  line at  $\lambda 3.0265 \mu$ . Since the expected width at half-power of the line is only about one quarter as large as the uncertainty in the wavelength determination, however, the possibility exists that the line is considerably attenuated before reaching ground.

In order to carry out a proper comparison between the observed and theoretical intensities of the lines, knowledge of the electron densities and temperatures prevailing



in the observed coronal regions would be required. White corona and optical emission line observations that may have been carried out by other observers of the November 12, 1966, eclipse might at a later date provide these data. At present and according to the remark made at the end of § IV, it is estimated in a very approximate manner that the line intensities corresponding to the quiet “smoothed-out” model corona near maximum of solar activity (Shklovskii 1965) are

$$I(\text{Si}^{9+}) = (0.5 - 1.0) \times 10^{-7} \frac{\text{watt}}{\text{cm}^2 \text{ sterad}}, \quad I(\text{Mg}^{7+}) = (1 - 2) \times 10^{-8} \frac{\text{watt}}{\text{cm}^2 \text{ sterad}}.$$

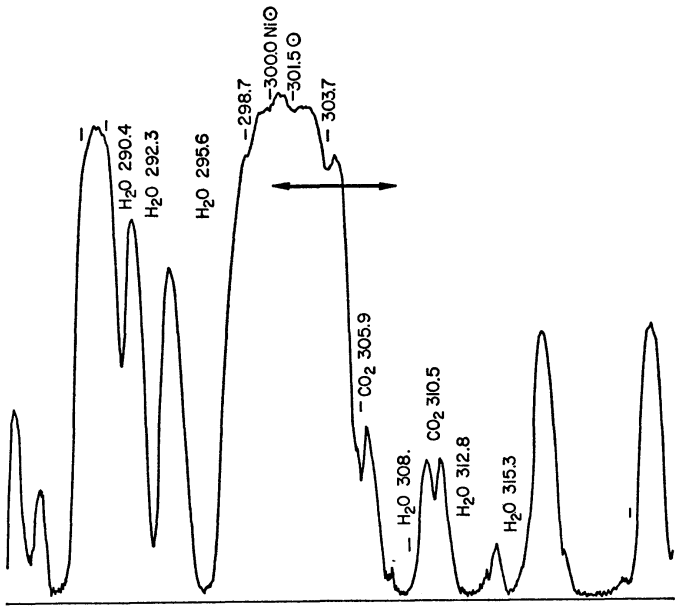


FIG. 5.—The observed wavelength of the [Si x] λ1.4305-μ line and its uncertainty are indicated by the bar with arrows drawn on the *Michigan Atlas of the Solar Spectrum* (Mohler, Pierce, McMath, and Goldberg 1955). The numbers identifying photospheric and telluric lines should be added to 14000 Å to obtain wavelengths in Ångstrom units.

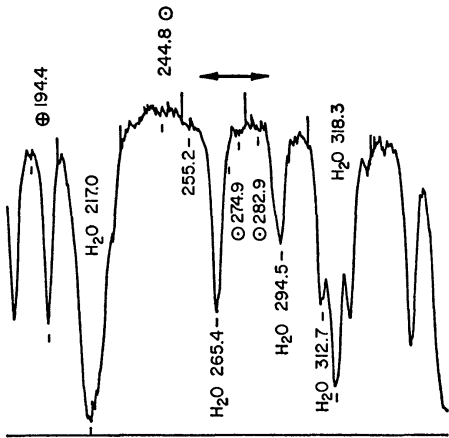


FIG. 6.—The observed wavelength of the [Mg viii] λ3.0275-μ line and its uncertainty are indicated by the bar with arrows drawn on the *Liège Atlas of the Solar Spectrum* (Migeotte, Neven, and Swensson 1957). The numbers identifying photospheric and telluric lines should be added to 30000 Å to obtain wavelengths in Ångstrom units.

The intensities of the lines calculated by Münch (1966) should be revised to take into account collisional deactivation and excitation by proton collision. It has been pointed out by Bahcall and Wolf (1967) that at a temperature of  $10^6$  ° K, the excitation rate of the [Mg VIII] line by proton collision is just about equal to that due to electron collisions. The increased rates for collisional transitions make the population of the upper level of the [Mg VIII] line approach its Boltzmann value, and the net increase in the line intensity is not large. Proton collisions do not become as important as electron collisions for the excitation of the [Si X] line below temperatures of  $2 \times 10^6$  ° K. The theoretical intensities are thus

$$I_{\text{phot}}(\text{Si}^{9+}) = 3 \times 10^{-7} \frac{\text{watt}}{\text{cm}^2 \text{ sterad}}, \quad I_{\text{phot}}(\text{Mg}^{7+}) = 0.36 \times 10^{-7} \frac{\text{watt}}{\text{cm}^2 \text{ sterad}}$$

when photospheric abundances are assumed and

$$I_{\text{cor}}(\text{Si}^{9+}) = 18 \times 10^{-7} \frac{\text{watt}}{\text{cm}^2 \text{ sterad}}, \quad I_{\text{cor}}(\text{Mg}^{7+}) = 1.6 \times 10^{-7} \frac{\text{watt}}{\text{cm}^2 \text{ sterad}}.$$

Within the large uncertainty which must be ascribed to the comparison between observations and theoretical calculations, inferences about abundances should be considered quite tentative. Nevertheless, taking the previous results at face value, it would appear that the abundances of silicon and magnesium indicated by the intensities of the [Si X] and [Mg VIII] infrared coronal lines are a full order of magnitude smaller than those derived from the analysis of the coronal spectrum in the far ultraviolet and instead agree approximately with the photospheric values.

The co-operation and help given to us by the personnel of the NASA Ames Research Center associated with the eclipse expedition are gratefully acknowledged. Our indebtedness is also due to Dr. R. Stockhausen of the NASA Goddard Space Flight Center for the loan of the  $\text{CaF}_2$  window. The preparation of the instrument package could not have been completed without the able assistance of Mr. David Vail, of the Physics Department, California Institute of Technology. This work has been in part supported by the National Aeronautics and Space Administration, under grant NsG-426 to the California Institute of Technology.

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